NEEMO 18-20: Analog Testing for Mitigation of Communication Latency during Human Space Exploration

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Abstract—**NASA Extreme Environment Mission Operations (NEEMO) is an underwater spaceflight analog that allows a true mission-like operational environment and uses buoyancy effects and added weight to simulate different gravity levels. Three missions were undertaken from 2014-2015, NEEMO's 18-20. All missions were performed at the Aquarius undersea research habitat. During each mission, the effects of communication latencies on operations concepts, timelines, and tasks were studied. METHODS: Twelve subjects (4 per mission) were weighed out to simulate near-zero or partial gravity extravehicular activity (EVA) and evaluated different operations concepts for integration and management of a simulated Earth-based science team (ST) to provide input and direction during exploration activities. Exploration traverses were preplanned based on precursor data. Subjects completed science-related tasks including pre-sampling surveys, geologic-based sampling, and marine-based sampling as a portion of their tasks on saturation dives up to 4 hours in duration that were designed to simulate extravehicular activity (EVA) on Mars or the moons of Mars. One-way communication latencies, 5 and 10 minutes between space and mission control, were simulated throughout the missions. Objective data included task completion times, total EVA times, crew idle time, translation time, ST assimilation time (defined as time available for ST to discuss data/imagery after data acquisition). Subjective data included acceptability, simulation quality, capability assessment ratings, and comments. RESULTS: Precursor data can be used effectively to plan and execute exploration traverse EVAs (plans included detailed location of science sites, high-fidelity imagery of the sites, and directions to landmarks of interest within a site). Operations concepts that allow for pre-sampling surveys enable efficient traverse execution and meaningful Mission Control Center (MCC) interaction across communication latencies and can be done with minimal crew idle time. Imagery and contextual information from the EVA crew that is transmitted real-time to the intravehicular (IV) crewmember(s) can be used to verify that exploration traverse plans are being executed correctly. That same data can be effectively used by MCC (across comm latency) to provide meaningful feedback and instruction to the crew regarding sampling priorities, additional tasks, and changes to the EVA timeline. Text / data capabilities are preferred over voice capabilities between MCC and IV when executing exploration traverse plans over communication latency.**

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1. INTRODUCTION

The NASA Extreme Environment Mission Operations (NEEMO) Project provides analog missions that send groups of astronauts, engineers, and scientists to live in the Aquarius underwater habitat for up to 2 weeks at a time. Aquarius is the world's only undersea research facility and is located ~3.5 miles off Key Largo, FL at a depth of 62 feet. NASA and the NEEMO project have used Aquarius since 2001. The habitat and its surroundings provide a convincing analog for space exploration. Living and working in the undersea environment allows participants (aka “aquanauts”) to experience some of the same challenges that there are on distance asteroids, planets (e.g. Mars), or the moons. The aquanauts are able to simulate living in a spacecraft and test extravehicular activity (EVA) techniques and exploration concepts for future space missions. The underwater environment has the benefit of enabling the aquanauts to simulate different gravity levels. On shore, mission control facilities allow streaming of audio, video, and data from the crew inside the habitat as well as while outside the habitat performing simulated EVAs; similarly, communication streams flow from mission control to the habitat. Latency can be introduced into the 2-way audio, video, and data streams to simulate the delays in communication that will occur when human venture into deep space. As an example, destinations such as Mars surface or its moon Phobos would introduce communication latencies with Earth from 4-22 minutes in each direction. The NEEMO missions discussed in this paper simulate the Mars system, which aligns with NASA’s Evolvable Mars Campaign (EMC). [1] [2] [3]

The paper will address the communication latency-related research conducted during three NEEMO missions; NEEMO 18 (July 2014, 9 days), NEEMO 19 (September 2014, 7 days), and NEEMO 20 (July 2015, 14 days). Each mission had 4 person aquanaut crews consisting of NASA and international (i.e. Japanese Space Agency, European Space Agency) astronauts and EVA engineers. Exploration traverses were executed on all three missions with simulated communication latencies of 5 and 10 min OWLT (one-way light time). These communication latencies were chosen to represent a short and intermediate latency relevant to the Mars system and to cross-over to studies performed in other analogs. [4]

Exploration Traverse Operation Concepts

During the Apollo missions, exploration traverses were planned in advance based on data and imagery gathered from precursor satellites and prior missions. [5] Those traverse plans were comprised of science sites with proposed paths between them as well as detailed EVA timelines that defined the tasks to be performed at each science site. [6]

The Apollo crews had significant training in geology and science tasks prior to their missions [7] and this will likely be the case for future Mars crew [8]s. Even with their extensive training, Apollo astronauts were further supported by a science team (ST) on Earth that was essential to the overall scientific success of the missions. [9] The input that could be provided by a ST took several forms: precursor plans for each science site, feedback during the EVA on science priorities based on new information provided by the crew, changes to the science plans between EVAs, and formulation of new science plans for future missions. The OWLT for the Apollo missions between the Earth and the Moon was minimal (~1.25 sec), which allowed for meaningful near real-time interaction with the ST during the EVAs without special consideration for data transmission times and thus without impacting efficiency or increasing crew idle time (idle time defined as time spent waiting for ground input). [10] As the OWLT increases for destinations such as the Mars system, achieving meaningful ST input during the EVA will be more challenging. [11]
Based on these challenges, one operations concept would be to assume nearly complete autonomy for execution of the science by the crew with a ground-based ST acting primarily as a passive observer, only providing opportunistic feedback across latency during the EVA to influence crew actions and scientific return. An alternate operations concept would be to design EVA timelines with built-in timing accommodations to allow for data transmission to the ST, data analysis and interpretation by the ST, and the return transmission of the ST input to the crew. A hybrid approach between these two operations concepts was studied during NEEMOs 18-20, incorporating a mixture of crew independent and dependent tasks being performed. This approach built upon the results from other analog tests such as those performed at Pavilion Lake Research Project [12] and NASA’s 2012 Research and Technology Studies [4]. The high-level objective of the NEEMO 18-20 missions was to continue the research to determine the acceptability of this hybrid approach and to identify the capabilities that would be needed to implement the operations concept for actual missions.

Operations Concept Assumptions – For exploration destinations such as Mars or Phobos, it is assumed that robotic precursor missions will have collected sufficient high quality imagery and precursor data to plan detailed exploration traverses to be performed by human crews. Based on the results of analysis and analog testing, the baseline architecture assumes a ground-based mission control center (MCC) and ST to provide overall flight control and science expertise, respectively. In-space architecture elements will include a habitat with intravehicular (IV) workstations to support EVA operations and one or more EVA-dedicated Space Exploration Vehicles (SEV). [4] [1] A communication architecture between these elements and a crew during EVA will support transmission of voice, video, still images, and data across communication latency between the destination and Earth. The main two-way communication path between the crew and MCC/ST will be through the IV crewmember(s); i.e. generally MCC/ST does not communicate directly to the EV crew but rather interacts with IV and then IV passes relevant information on to the EV crew. However voice, video, still images, and data from the EV crew does transmit directly to both IV (real-time) and to MCC/ST (across latency).

During EVA execution, information will be obtained through pre-sampling surveys of each targeted science site along a traverse; those presampling surveys will provide additional and higher resolution data than was obtainable from precursor missions. It is assumed that while the crew will have significant science training, a higher level of science expertise and/or analysis capabilities will exist in a ground-based ST. The pre-sampling survey data can be used by the ST to provide input to the crew through modification of science priorities, science tasks, and/or to modify traverse plans and maximize the quality of the science achieved. It is assumed that EVA timelines can be designed to allow for the ST input to occur through integration of ground independent and ground dependent tasks while minimizing crew idle time.

Timeline Design Approaches

To allow for ground-based ST interaction with crews during EVA under latency constraints, special consideration must be given to EVA timeline design. There must be a clear delineation between which EVA tasks can be done independently of MCC/ST interaction vs. those tasks that are either dependent on ground input or could substantially benefit from ground interaction. For tasks that are dependent on ground input, dependent task groups can be created and distributed throughout the timeline. For instance, a dependent task group could consist of a pre-sampling survey of a science site based on precursor plans, which can be performed independent from ground input, and a follow-on sampling task of that science site that is dependent on ground input. Other tasks in the timeline can be decoupled from the dependent task group(s) and may be performed stand-alone, independent from ground input. With sufficient understanding of EVA task durations, dependencies, OWLTs and the amount of time needed by the ground to provide meaningful input for dependent tasks, timelines can be created that allow for ground input while minimizing crew idle time. This necessarily includes adequate separation of dependent tasks in a dependent tasks group. As a result, the timeline may be structured by interleaving dependent task groups with independent tasks to fill available time between dependent tasks to utilize the time that would be otherwise spent waiting on round-trip data transfer.

Figure 1 depicts an example of an EVA timeline designed with both dependent task groups and stand-alone tasks. For instance, Task A - Parts 1 and 2 represent a dependent task group in which the first part is performed independent of the ground (e.g. pre-sampling survey) and the second part depends on ground input to execute (e.g. sampling). In between the two task parts in this group, data from the first part reaches the ST across latency and ground assimilation time (GAT) is allocated for the ST to analyze the data and formulate input. ST input is then sent from the ground to the crew before the input is needed to start Part 2 of the dependent task group. The sample timeline also depicts the interleaving of multiple dependent task groups, as well as the insertion of stand-alone tasks to allow for coordinated interactions without idle time between the crew and MCC. This approach to timeline design is meant to facilitate ground interactions in the presence of communication latency to minimize crew idle time.

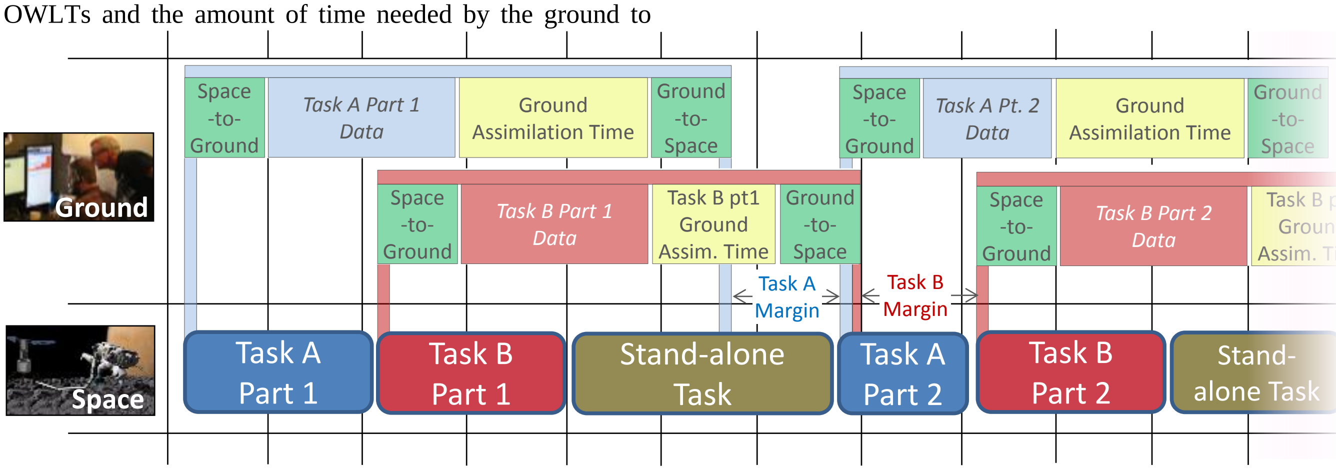

Figure 1 - EVA timeline designed with dependent task group approach and stand-alone tasks.

Totally Acceptable		Acceptable		Borderline		Unacceptable		Totally Unacceptable		No Rating
No improvements necessary		Minor improvements desired		Improvements warranted		Improvements required		Major improvements required		Unable to assess capability
1	2	3	4	5	6	7	8	9	10	NR

Essential / Enabling		Significantly Enhancing		Moderately Enhancing		Marginally Enhancing		Little or No Enhancement		No Rating
Impossible or highly inadvisable to perform mission without capability		Capabilities are likely to significantly enhance one or more aspects of the mission		Capabilities likely to moderately enhance one or more aspects of the mission or significantly enhance the mission on rare occasions.		Capabilities are only marginally useful or useful only on very rare occasions		Capabilities are not useful under any reasonably foreseeable circumstances.		Unable to assess capability
1	2	3	4	5	6	7	8	9	10	NR

Figure 2 - Acceptability and capability assessment rating scales.

2. Research Questions and Study Design

The NEEMO 18-20 research questions addressed in this paper were focused on assessing operations concepts and capabilities for having meaningful space-ground interactions during an EVA, even in the presence of communication latency. They can be summarized as:

- Are the mission operations concepts, science operations concepts, and communications protocols under consideration for different exploration mission destinations acceptable? What improvements are desired, warranted, or required?
- Do mission operations concepts, science operations concepts, and communications protocols remain acceptable as communications latency increases up to 10 minutes one-way light time (OWLT)? What improvements are desired, warranted, or required?

To investigate these research questions, exploration traverses were designed and executed during all three NEEMO missions using the aforementioned baseline operations concept. During NEEMO 18, 5 and 10 minute OWLTs were simulated; additional independent variables were voice-only or text-only constraints on IV-MCC/ST interactions, but data transmission (e.g. annotated images) was allowed under both conditions. During NEEMO 19, only a 10 minute OWLT was performed and there were no restrictions on voice, text, or data capabilities between IV and MCC/ST. NEEMO 20 was executed with 5 and 10 minute OWLTs, also with no restrictions on voice, text or data capabilities. During NEEMO 20, different methods of assigning GAT to the ST were studied. The concept of GAT was present for NEEMO 18 and 19, but the input from the ST was strictly predetermined requiring no data synthesis during EVA execution. For NEEMO 20, the ST was asked to formulate input real-time based on the data being received from the EV crew. With this added fidelity, different methods of assigning GAT were assessed; a fixed GAT of 5 minutes (in addition to the time that it takes for data to stream to the ST; 5 minutes selected as a first estimate of the necessary time that was minimally impactful to the timeline design), and a dynamic GAT that enabled the ST to process and interpret the steaming data as long as their input reached the crew by the time it was needed. Thus, during the dynamic GAT condition if the crew was behind in the timeline, the ST could take longer to formulate input; alternately if the crew was ahead in the timeline, the ST was forced to formulate input more quickly so as not to create idle time for the crew, including possibly making decisions based on incomplete information if sufficient time was not available to review all of the incoming data.

During all three missions, the study team consistently applied a set of field-tested evaluation techniques that use surveys of acceptability and capability assessment ratings (Figure 2), which incorporated individual and consensus ratings of the EV crew, IV crew, and ground-based teams. This assessment methodology has been used during several previous PLRP, RATS and NEEMO field tests [13-15] [16]. Initial ratings and associated recommendations were recorded individually by team-members. Overall consensus ratings and recommendations were then discussed and agreed upon by crewmembers and the MCC/ST team in post-EVA consensus meetings. An additional opportunity to discuss and adjust consensus ratings was provided at post-mission debriefs. Additional data sources included console operator notes and EVA performance criteria duration of tasks, idle time, and communication content.

3. Methods

The baseline operation concept was executed on all three missions with simulated milligravity and partial gravity EVAs up to 4 hours in duration. One half day of EVA-focused classroom-based training was provided to each crew several weeks in advance of each mission in which the objectives, study design, and methods were described. Additional field-based training took place for each crew in the week preceding each mission, with a few hours of hands-on time with all the required equipment and procedures prior to mission start; this time was limited due to required training in dive and habitat systems and training for other investigations taking place during the missions.

There were two EVA crewmembers on all EVAs and one dedicated IV crewmember inside Aquarius supporting the EVA. Mission control and science teams were staffed to support all EVAs. The EVAs included exploration traverses that were designed on the seafloor in the vicinity of Aquarius, incorporating multiple science sites; simulated geologic sites (NEEMO 18-20), simulated marine science sites (NEEMO 19) and actual marine science sites (NEEMO 20). NEEMO 20 marine sciences were selected and explored based on *actual* scientific research objectives, as opposed to NEEMO 19 where the scientific investigation of marine sites was fabricated for the simulation. The marine science activities served as surrogate astrobiology research activities. Crew translation modes between science sites varied by mission and EVA environment. For the milligravity environment, booms were used and for partial gravity, the crew used ambulation or diver propulsion vehicles Capabilities and products for executing the baseline operations concept are described in the following subsections.

Mission Control Center

The Information Technology and Communications Directorate (ITCD) at Kennedy Space Center (KSC) partnered with Florida International University's (FIU) Aquarius Reef Base (ARB) and the NASA analog team, provided a mission control center (MCC) during all three missions. The MCC provided:

- Multi-path infrastructure including video, audio, network / data sharing, and data management
- Console operators including mission director, EVA, planners, Public Affairs Office (PAO), Capsule Communicator (CAPCOM)
- Certified ISS mission planners executing a flight plan using Playbook (defined in later section)
- Daily execute notes, operations notes, and planning product updates
- "Flight-like" procedures for EVA, science, etc.
- Dedicated science team working area

Dive Systems

The dive system used by the EV crew during the missions was the Super-Lite 37 umbilical-based dive system (Figure 3). The SL-37 or similar systems have been used extensively at previous NEEMO missions and numerous other undersea operations. The crews were hardwired to the Aquarius habitat via umbilical to mediate data and oxygen supply transfer. The umbilical enabled 2-way voice communication capability between the habitat/MCC and the EV crew. Cameras on the helmets provided streaming video from the EV crew to the IV crew, MCC, and ST.

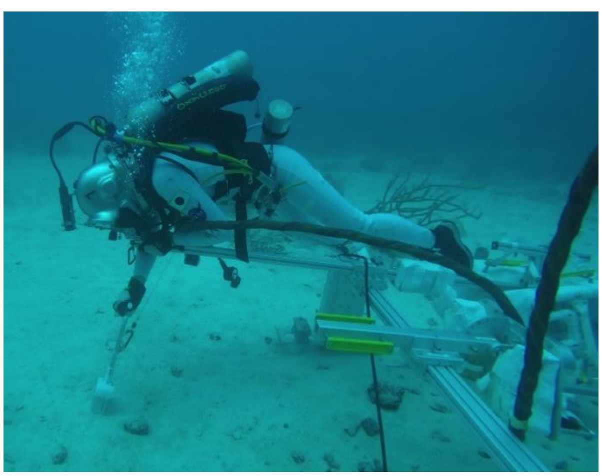

Figure 3 - EVA crewmember performing sampling task in SL-37 dive system w/ helmet-mounted video camera.

IV Workstation

Within Aquarius, a dedicated IV workstation that included real-time, 2-way voice communication with the EV crew outside of the habitat was utilized. The IV operator had EV crewmember point-of-view video thanks to mounted helmet cameras as well as a bird's eye perspective of crew and worksite provided by fixed situational awareness cameras (Figure 4). Multiple laptop computers and tablets were available to the IV crew for guiding the EV crew through the EVA timelines, procedures. Interaction with the ground was mediated via texting using Playbook© and/or voice using Voxer© and Vcomm©, over the simulated OWLT.

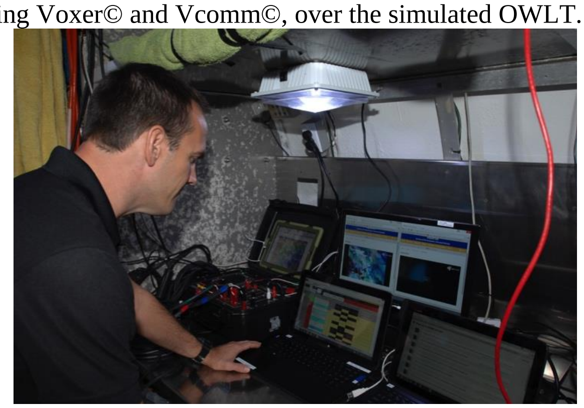

Figure 4 - Aquarius IV workstation.

EVA Traverse Maps and Plans

All EVA support tools, such as traverse maps and detailed procedures, were created using precursor data and were utilized for all EVAs. These materials defined the specific geospatial location of each science site/zone in relation to known landmarks and articulated the required procedures for successful task execution. Figure 5 shows a Phobos EVA traverse map used during NEEMO 20, where the crew leveraged a prototype Phobos boom to conduct scientific activities in predefined science work zones. Figure 6 shows a crew perspective EVA plan of the same plan articulated in Figure 5 with precursor science targets overlaid with priority annotations developed by the ST.

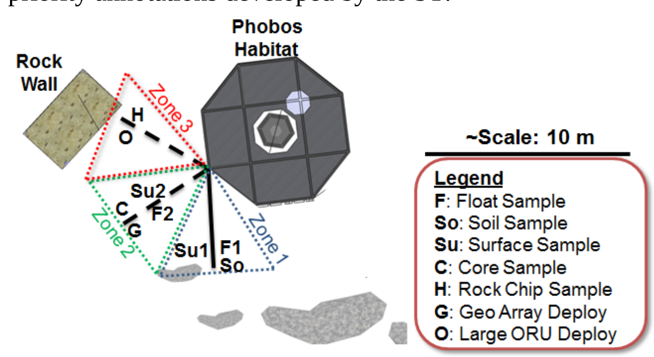

Figure 5 – Example precursor traverse map from NEEMO 20.

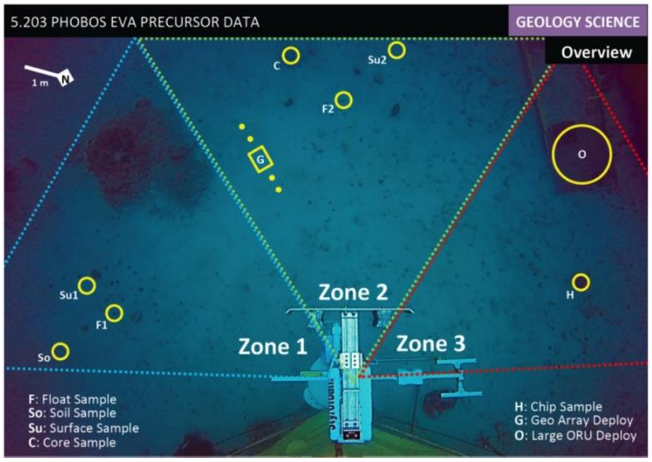

Figure 6 - Example precursor plan from NEEMO 20.

Temporary Markers

Temporary markers were used during pre-sampling surveys to clearly mark areas of interest based on precursor data (Figure 7). They also served as a reference frame to which the ST could direct their sampling recommendations and priorities. During the pre-sampling surveys, EV crewmembers placed the temporary markers according to the precursor data plan and then centered their helmet camera field-of-view on these locations to provide detailed images of the surrounding areas to the ST.

Figure 7 - Temporary markers (example from NEEMO 20) used to identify potential samples during pre-sampling surveys. (Image credit: NASA)

Playbook

The Playbook© planning tool, created by Ames Research Center, has heritage back to the Mars Exploration Rover mission, the Phoenix Mars Lander mission, the Mars Science Laboratory, and ISS crew activity planning by ground controllers at Johnson Space Center. Playbook allows the crew and controllers to view and manipulate time-lined mission activities, transfer text and images via a texting client called the Mission Log, and access procedures for all mission activities. The Mission Log was used during the EVAs as the main method of sending text and data (e.g. annotated images; Figure 9) between IV and MCC/ST, with the exchange of information delayed based on the imposed latency.

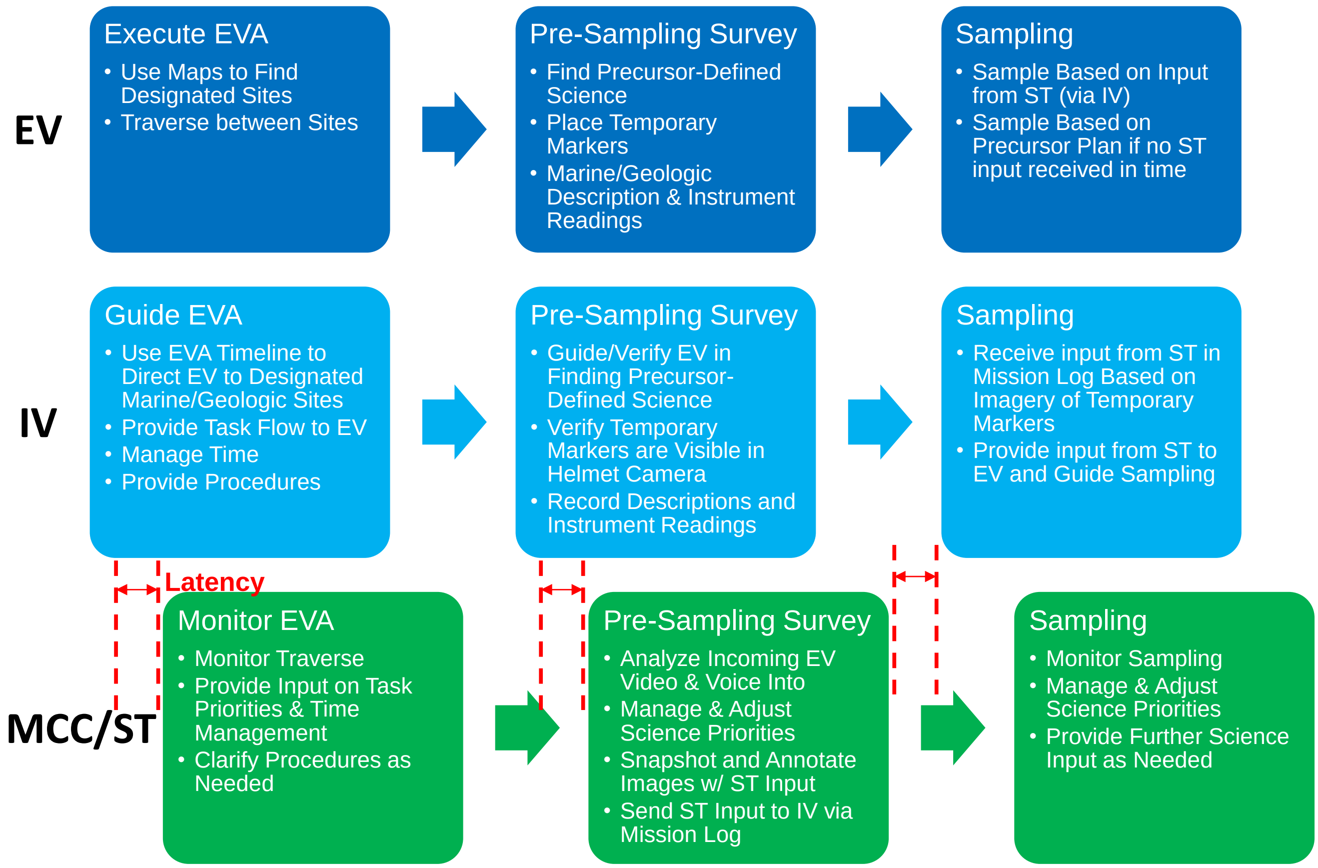

Figure 8 - Baseline operations concept traverse and science flow.

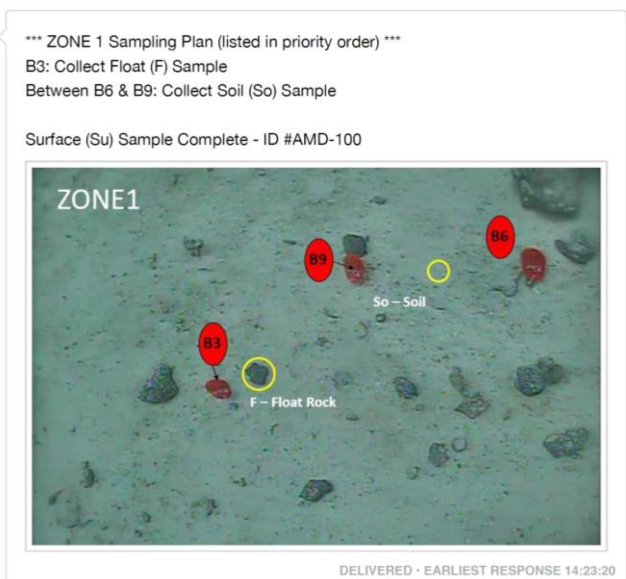

Figure 9 - Example annotated message sent from ST to IV to convey ST science priorities during EVA.

EVA Process Flow

EVA timelines followed the general process flow depicted in Figure 8. Each EVA was operated by an IV crewmember and two EV crewmembers. The MCC and ST monitored the EVAs and provided input in terms of mission and science priorities. The EVAs were executed using the precursor-defined traverse maps and science plans. The EV crew used the temporary markers to mark areas for potential sampling and used helmet video cameras to image the temporary markers once placed alongside the samples of interest. The ST (across latency) captured still images from the helmet camera video, annotated those images with sampling recommendations (Figure 9), and sent them back to IV to convey ST sampling priorities. IV then worked with EV to incorporate the ST input for the subsequent sampling tasks.

EVA Timelines

Detailed EVA timelines (Figure 10) were designed based on the general EVA process flow and implemented in Playbook for each EVA. The timeline design approach described earlier was used, i.e. interleaving dependent task groups, incorporating independent tasks, and accounting for task durations. Task durations for the EVA timelines were estimated based on prior experience with the tasks and consultation with field scientists. Based on the estimated times, gaps were designed between tasks in a dependent task group to allow for transmission of pre-sampling survey data to MCC/ST, time for assimilation of the data by the ST (GAT) and sending of input for the associated sampling task, and transmission time from MCC/ST to the crew.

PET	EV1	EV2
0:05	Egress, Weighout, Translate to Starting Point	
0:10		
0:15	Predeploy Yaw Phobos boom (zone 1); Deploy Boom	
0:20	Pre-Sampling Survey (zone 1)	Surface Sample (zone 1)
0:25	Yaw Phobos Boom to Zone 2	
0:30	Surface Sample (zone 2)	Pre-Sampling Survey (zone 2)
0:35	Yaw Phobos Boom to Zone 3	
0:40	Pre-Sampling Survey (Zone 3)	
0:45	Yaw Phobos Boom to Zone 1	
0:50	Soil Sample (zone 1)	Float Sample (zone 1)
0:55	Yaw Phobos Boom to Zone 2	
1:00	Float Sample (zone 2)	Core Sample (zone 2)
1:05	Yaw Phobos Boom to Zone 3	
1:10	Rock Chip Sample (zone 3)	
1:15	Deploy Geophysical Array	
1:20		
1:25		
1:30	Yaw Phobos Boom (to zone 3)	
1:35	Deploy Large ORU (includes unstowing, transporting, install microspine anchors, and deploying ORU)	
1:40		
1:45		
1:50		
1:55	Return to Hab, Cleanup, & Ingress	Return to Hab, Cleanup, & Ingress
2:00		

Figure 10 – Example EVA timeline with 5 minute OWLT communication latency; dependent tasks grouped by color.

4. Results & Discussion

Each mission varied in the number of EVAs and EVA hours dedicated to operations concept research summarized as follows:

- NEEMO 18: 4 EVAs, 12 hours total
- NEEMO 19: 3 EVAs, 12 hours total
- NEEMO 20: 10 EVAs, 32 hours total

The number of dependent task interactions varied by EVA but were designed around visiting and revisiting science sites or landmarks to perform pre-sampling surveys and sampling, respectively.

Acceptability of the Operations Concept

NEEMO 18 and 19 crews provided operational acceptability ratings for the overall operations concept. Both the NEEMO 18 and 19 crews rated the operations concept "totally acceptable" (Figure 11; reference Figure 2 for rating scales). The crews provided no differences in their acceptability based on any of the independent variables (i.e. 5 vs. 10 min OWLT or any restrictions on voice vs. text vs. voice + text).

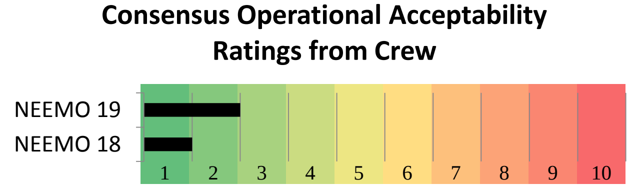

Figure 11 – Operations concept consensus acceptability ratings from the crews of NEEMO 18 and 19; reference Figure 2 for details on scales.

Since the ST input for NEEMO 18 and 19 was simulated (i.e. effectively zero GAT), no ST consensus ratings were gathered. For NEEMO 20, in which the ST input was formulated real-time after receipt of the pre-sampling survey data from the crew, ST consensus acceptability ratings were collected. The NEEMO 20 ST rated the dynamic GAT condition more acceptable than the fixed GAT condition for both 5 and 10 min OWLT (Figure 12).

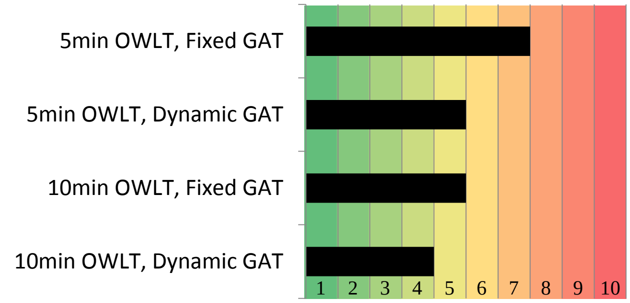

Figure 12 - NEEMO 20 science team consensus operations concept acceptability ratings; reference Figure 2 for details on scales.

Fixed GAT- The ST stated that much better data synthesis tools are required in order to produce an answer within the fixed GAT of 5 minutes allotted during NEEMO 20. Much of the ST efforts and attention was spent sifting through recorded video from the EV crew helmet cameras and capturing an appropriate image for annotation and upload of input, rather than spent synthesizing the imagery of interest. Overall, there was less time assimilating the data and more time acquiring meaningful context imagery and generating a product containing ST input for upload. The ST stated that the only realistic influences a ST can have on EVA execution under a 5-minute fixed GAT condition using the tools provided during NEEMO 20 are likely limited to predefined target option selection. For example, if there are 4 precursor-identified targets and the ST input is to pick two of the four targets based on the data from the EV crew. Any influence of action that is not aligned with the precursor data is difficult to convey with the tools used (mission log) within the time available. *A priori* decision making requirements and associated information is critical to making fixed GAT a feasible option.

Dynamic GAT- The ST stated that the dynamic GAT condition provided a more reasonable time period to synthesize data because they could track timeline progress and delay sending input until it was needed. By delaying ST input, the ST could refine their priorities, and articulate their input more succinctly. Coincidently, dynamic GAT was the preferred option during NEEMO 20 given that nearly all tasks performed took longer than expected, thus giving more time for the ST. The ST stated there is a possible compounding effect however; i.e. if the ST takes more time to synthesize the data, the more likely it would be to include more tasks/samples for the crew to perform, which would further impact and likely delay EVA timeline progress further. Also, had the crew been ahead in the timeline, the dynamic condition as executed could have been worse than the 5min fixed GAT condition, i.e. requiring quicker decisions to be made. Consideration could be given to hybrid approaches including those that may limit that amount of idle time to as set amount, followed by proceeding with precursor plans.

Capabilities Assessment

Key capabilities for execution of the operations concept were assessed by the crews (NEEMO 18-20) and ST (NEEMO 20). Figure 13 shows the capabilities assessment ratings provided; reference Figure 2 for ratings scale descriptions.

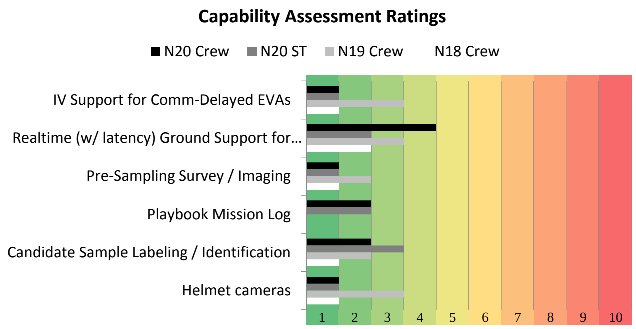

Figure 13 - NEEMO 18-20 crew and science team consensus capability assessment ratings; reference Figure 2 for details on rating scales.

IV support for the EVAs as a means of distilling science team input and providing it to EV as well as guiding EV in capture of imagery to provide to the ST was rated essential by the NEEMO 20 ST and most crews. Furthermore, it was noted that incorporating a dedicated Science IV crewmember to focus solely on the scientific aspects of the EVA (e.g. science payloads, samples, data collection, etc.) would be highly beneficial. This addition would allow for superior task sharing with the other IV crewmember, who could then attend to the more traditional EVA tasks (e.g. timeline management and procedure support). However, additional personnel also requires an additional layer of coordination by the IV operators beyond what the currently baseline operations concept examined.

Support from the ground to execute the operations concept was rated essential by the NEEMO 20 ST and most crews. Pre-sampling surveys and imaging were rated as essential for execution of the operations concept by all crews and the NEEMO 20 ST. A tool with the capability to send text and annotated images was rated as essential to execution of the operations concept. A method of unambiguously marking candidate samples was rated as essential or significantly enhancing by all crews and the NEEMO 20 ST. A helmet camera capability for the EV crew to use to capture marked candidate sample areas was rated as essential or significantly enhancing by all crews and the NEEMO 20 ST.

Pre-Sampling Survey and Ground Assimilation Times

The EVA timeline design process estimated the time of completion for tasks such as pre-sampling surveys. During NEEMO 18 and 19, pre-sampling surveys were simple tasks that only required identification of straightforward sample information or measurements (such as ruler dimensions and color). For NEEMO 20, EV crew were required to provide more advanced sample description, thus making the scientific tasks more realistic but also more susceptible to training effects. Figure 14 shows an example of the planned vs. actual pre-sampling survey times for 4 EVAs near the start of the NEEMO 20 mission. This example shows that the majority of pre-sampling survey times ran longer than expected, with the longest times during the first EVA. Training effects due to limited familiarization time with equipment and methods are the reason for substantially longer pre-sampling times on EVA 3.

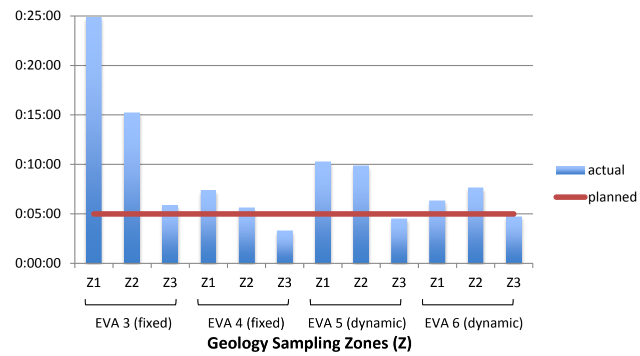

Figure 14 - Time for crew to complete geology pre-sampling survey during NEEMO 20 Phobos EVAs.

Figure 15 shows a representative example of the actual GAT vs. planned GAT during NEEMO 20's fixed GAT EVAs. The fixed GAT for NEEMO 20 was limited to 5 minutes. The plot shows that although 5 minutes was allotted for data synthesis, at least 10 minutes was taken to formulate the ST input and send a response to the crew. The general perception from the ST was that the process for capturing an image from recorded video, annotating it and uploading it to the mission log could not be done quicker, and the longer the pre-sampling survey time, the longer it took to select an image for annotation.

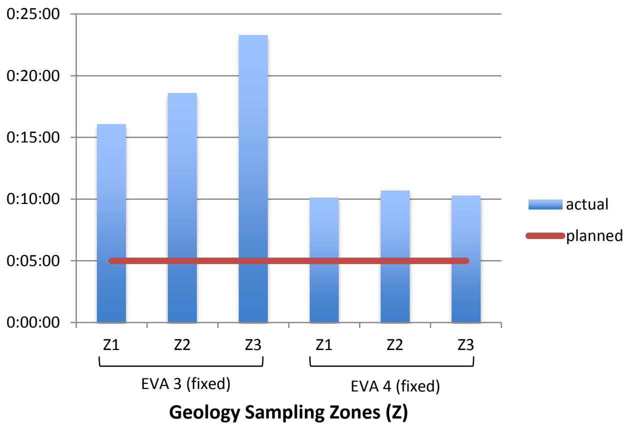

Figure 15 - Actual vs. planned ground assimilation time (GAT) during NEEMO 20 Phobos EVAs.

Figure 16 shows representative data for the NEEMO 20 dynamic GAT cases. When the ST realized that the crew were running behind schedule, they took advantage of the additional time when operating in the dynamic GAT case. Note that all dynamic GAT durations are longer than the fixed GAT time of 5 minutes.

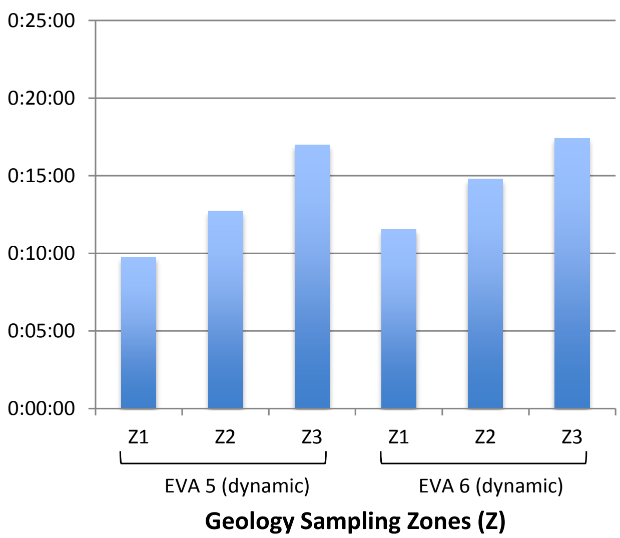

Figure 16 - Actual ground assimilation time (GAT) during NEEMO 20 dynamic GAT Phobos EVAs.

Study Limitations

While each the overall operations concept proved effective, there exists numerous challenges and areas of improvement for future analog studies to increase the fidelity of the results. In particular to NEEMO 20 operations, the inclusion of actual scientific objectives in the form of marine science activities imposed a higher degree of required crew expertise and ST/IV support tool functionality. Crew training will need to become more comprehensive, including the specific scientific nuances associated with proper sample survey and collection in addition to more traditional EVA task procedures. From an ST perspective, incorporating a more capable data synthesis environment and chain of authority will be paramount. The limited number of personnel in the ST during NEEMO 20 artificially streamlined the scientific data synthesis process. Future human spaceflight missions will likely include many competing ST science objectives all of which will need to be managed during EVA to ensure the crew is meeting objectives.

5. CONCLUSIONS

1. Precursor data can be used effectively to plan and execute exploration traverse EVAs

2. Operations concepts that allow for pre-sampling surveys enable efficient traverse execution and meaningful ST interaction across communication latencies

   – Capabilities that provide imagery and information from the EVA crew real-time to IV can be used to verify exploration traverse plans

   – That same data can be effectively used by ST (across comm latency) to provide further instructions to the crew on sampling priorities, additional tasks, and changes to plans

3. Continuous and meaningful MCC/ST input is achievable during exploration traverses, even with long communication latencies up to 10 minutes.

4. Dynamic approaches to GAT are preferred over fixed when timeline tasks take longer than expected.

   – While a fixed GAT guarantees time for the ground to assimilate science data, the 5 minutes allotted during NEEMO 20 was insufficient given the tools provided.

   – A dynamic approach to GAT allows the ST to take more time to provide input when the crew is behind on the timeline, thus providing more potential for maximizing science

   – When timeline tasks are taking less time than expected, a dynamic approach would require quicker response by the science team and would be less favorable

5. Hybrid approaches to planning exploration EVAs that include some degree of crew autonomy should be considered

   – Continue operations concepts research into hybrid approaches that balance crew autonomy based on precursor data/plans and methods for incorporation of science team input on tasks where there can provide benefit
   – EV and IV training is paramount. More specifically, the science intent must be well understood so that EV/IV crew can make calls in

real-time if necessary to meet science objectives.

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